

Intercomparisons of Trace Gases Profiles from the Odin/SMR and Aura/MLS Limb Sounders

B. Barret,¹ P. Ricaud,¹ M. L. Santee,² J.-L. Attié,¹ J. Urban,³ E. Le

Flochmoën,¹ G. Berthet,⁴ D. Murtagh,³ P. Eriksson,³ A. Jones,³ J. de La

Noë,⁵ E. Dupuy,^{5,6} L. Froidevaux,² N. J. Livesey,² J. W. Waters,² M. J.

Filipiak⁷

B. Barret, Laboratoire d'Aérologie, CNRS, 14 avenue Edouard Belin, Toulouse, 31400, France.

(brice.barret@aero.obs-mip.fr)

¹Laboratoire d'Aérologie, Observatoire de
Midi-Pyrénées, Toulouse, France.

²Jet Propulsion Laboratory, California
Institute of Technology, Pasadena,
California, USA.

³Department of Radio and Space Science,
Chalmers University of Technology,
Göteborg, Sweden.

⁴Laboratoire de Physique et Chimie de
l'Environnement, Orleans, France.

⁵Observatoire Aquitain des Sciences de
l'Univers, L3AB, Floirac, France.

Abstract. This paper presents the intercomparison of O_3 , HNO_3 , ClO , N_2O and CO profiles measured by the two spaceborne microwave instruments MLS (Microwave Limb Sounder) and SMR (Sub-Millimetre Radiometer) on-board the Aura and Odin satellites respectively. We compared version 1.5 level 2 data from MLS with level 2 data produced by the French data processor version 222 and 225 and by the Swedish data processor version 2.0, for several days in September 2004 and in March 2005. For the 5 gases studied, an overall good agreement is found between both instruments. Most of the observed discrepancies between SMR and MLS are consistent with results from other intercomparison studies involving MLS or SMR. O_3 profiles retrieved from the SMR 501.8 GHz band are noisier than MLS profiles but mean biases between both instruments do not exceed 10%. SMR HNO_3 profiles are biased low relative to MLS's by $\sim 30\%$ above the profile peak. In the lower stratosphere, MLS ClO profiles are biased low by up to 0.3 ppbv relative to coincident SMR profiles, except in the southern hemisphere polar

⁶Now at University of Saskatchewan,
Saskatoon, Saskatchewan, Canada.

⁷Institute of Atmospheric and
Environmental Science, School of
Geosciences, University of Edinburgh,
Edinburgh, UK.

vortex in the presence of chlorine activation. N₂O profiles from both instruments are in very good agreement with mean biases not exceeding 15%. Finally, the intercomparison between SMR and MLS CO profiles have shown a good agreement from the middle stratosphere to the middle mesosphere in spite of strong oscillations in the MLS profiles. In the upper mesosphere, MLS CO concentrations are biased high relative to SMR while negative values in the MLS retrievals are responsible for a negative bias in the tropics around 30 hPa.

1. Introduction

Satellite measurements are very important for monitoring the evolution of the composition of the Earth's atmosphere on a global scale and for understanding its impact on climate changes. Observations from space need to be validated by correlative measurements from ground-based, airborne, balloon-borne and from other spaceborne instruments to assess their quality. Furthermore, individual satellites or instruments have a limited lifetime from less than a year to about a decade. The building of meaningful long term observational time series therefore requires careful checking of the consistency between the measurements from the different instruments. The intercomparison of observations from different spaceborne instruments is therefore essential.

In the past decades, a number of satellite missions dedicated to the observation of the atmosphere have been successfully operated. The Odin satellite launched on 20 February 2001 is among these. The Sub-Millimetre Radiometer (SMR) instrument onboard Odin shares observation time equally between an aeronomy mode and an astronomy mode. In aeronomy mode, the main objective of SMR is to study stratospheric and mesospheric chemistry and dynamics through the determination of relevant trace constituent profiles such as O_3 , ClO , N_2O , HNO_3 , CO , H_2O , NO , HO_2 , as well as H_2O and O_3 isotopes [e. g., *Murtagh et al.*, 2002, *Merino et al.*, 2002, *Urban et al.*, 2006a]. The Microwave Limb Sounder (MLS) is one of the four instruments onboard the Earth Observing System (EOS) Aura satellite launched on 15 July 2004. The main objectives of the EOS Aura mission are to monitor the evolution of the stratospheric ozone layer and to study the processes controlling tropospheric pollution and the impact of atmospheric composition changes on

climate [*Schoeberl et al.*, 2006]. Aura/MLS contributes to these objectives by measuring atmospheric profiles of temperature and of more than a dozen of constituents from the troposphere to the mesosphere [*Waters et al.*, 2006]. In order to determine the composition and the temperature of the Earth's atmosphere SMR and MLS both measure the thermal emission at the Earth's limb in the microwave domain.

Since the first Aura/MLS observations in August 2004, both instruments have been simultaneously measuring the abundances of a common set of stratospheric gases. This paper is dedicated to the intercomparison of vertical profiles of O₃, HNO₃, ClO, N₂O and CO measured by SMR and MLS in two different seasons (boreal and austral springs). Section 2 and 3 briefly describe the SMR and MLS instruments and observations. The intercomparisons are described and discussed in detail in Section 4. Finally, a summary of the results and the conclusions are presented in Section 5.

2. The SMR Observations

The Odin satellite is placed in a sun-synchronous, near polar and circular orbit at ~600 km altitude with an inclination of 97.8° and an ascending node at 18:00 hours (local time). In its aeronomy mode, SMR measures the sub-millimeter thermal emission at the Earth's limb with a 1.1 m telescope. It covers the 486-581 GHz spectral range with 4 tunable single-sideband Schottky diode heterodyne receivers and two high-resolution autocorrelator spectrometers [*Frisk et al.*, 2003]. Measurements are performed about two days per week in two bands at 501.8 and 544.6 GHz and one to two days per month in a band centered at 576.9 GHz.

In its stratospheric mode SMR scans the atmospheric limb from 7 to 72 km with an integration time for the recording of a single spectrum ranging from 0.875 s (~1.5 km vertical

spacing) in the stratosphere (below 50 km) to 3.5 s (~ 6 km vertical spacing) in the mesosphere and enables the retrieval of vertical profiles of O_3 , N_2O and ClO in the 501.8 GHz band and of O_3 and HNO_3 in the 544.6 GHz band. The SMR strato-mesospheric mode has an upper scan limit extended to 110 km and an integration time increased from 0.875 s to 3.5 s around 70 km, and enables the retrieval of CO and O_3 profiles in the 576.9 GHz band. Consecutive scans are recorded with a 500 km horizontal spacing along the satellite track. The choice of the 486-581 GHz spectral range for SMR prevents retrievals at and below the tropopause level because of the strong water vapor continuum proceeding from the 556.9 GHz water vapor line.

Detailed information on level 1 SMR data processing are given in *Olberg et al.* [2003]. Retrievals are performed by two similar data processors in France and Sweden. The Chalmers University (Gothenburg, Sweden) is in charge of the systematic production of the Odin/SMR level-2 data product. The French data processor CTSO (Chaîne de Traitement Scientifique Odin), formerly operated at the Observatoire Aquitain des Sciences de l'Univers (Bordeaux, France) and now at Laboratoire d'Aérodynamique (Toulouse, France), aimed initially at the verification and validation of the operational level-2 data produced in Sweden, but is now used as full scientific processor. The retrieval algorithms, based on the Optimal Estimation Method [*Rodgers*, 1976], are described in e.g. *Baron et al.* [2002], *Merino et al.* [2002], *Eriksson et al.* [2002,2005] and *Urban et al.* [2004a]. A detailed and updated description of stratospheric trace gases (ClO , N_2O , HNO_3 and O_3) retrievals from SMR by both processors is given in *Urban et al.* [2005b]. In this study we use retrievals from the CTSO for the measurements at 501.8 GHz (latest version: 222) and 576.9 GHz (latest version: 225) as well as data produced by the Chalmers level-2 processor for the

544.6 GHz band (latest version: v2.0). The SMR products that are used in this study are summarized in Table 1.

3. The MLS Observations

The Aura satellite is in a sun-synchronous orbit (98° inclination) at ~ 705 km with an ascending node at 13:45 hours (local time). The MLS instrument observes the millimeter and submillimeter thermal emission from the atmospheric limb in broad spectral regions centered at 118 (R1), 190 (R2), 240 (R3) and 640 (R4) GHz and 2.5 THz (R5) with heterodyne radiometers. The instrument and its calibration are discussed in *Pickett* [2006], *Cofield and Stek* [2006] and *Jarnot et al.* [2006]. Vertical profiles of 17 target atmospheric parameters, among which 14 trace gases, are retrieved from the MLS observations with a 165 km horizontal spacing [*Waters et al.*, 2006]. The retrieval methodology for the MLS observations, also based on the optimal estimation, is described in detail in *Livesey et al.* [2006]. The new concept implemented in the MLS retrieval algorithm is a 2D approach allowing retrieval of atmospheric structures in both the vertical and line of sight directions taking into account the overlapping regions covered by consecutive scans.

For the version 1.5 of MLS data used in the present work, ClO and N₂O are retrieved from the R4 radiometer, O₃ and CO from the R3 radiometer and HNO₃ from the R3 radiometer at and below 10 hPa and from the R2 radiometer at and above 6.8 hPa (see Table 1). A detailed description of the characteristics of these products can be found in the "EOS MLS Version 1.5 Level 2 data quality and description document" [*Livesey et al.*, 2005].

4. Comparison of Trace Gases Profiles

4.1. Intercomparison Approach

Given that MLS is sampling the atmosphere at a higher rate than SMR, each SMR profile is matched to the average of all MLS coincident profiles. In order to estimate the impact of the coincidence criteria upon the intercomparison results, we have tested two sets of criteria. In the first case MLS profiles are estimated coincident with a SMR profile if they are measured within $\pm 10^\circ$ longitude and $\pm 2.5^\circ$ latitude around the SMR measurement location and within ± 12 hours from its measurement time. In the second case, the spatial criteria are reduced to $\pm 5^\circ$ longitude and $\pm 1.5^\circ$ latitude and the temporal criterion is reduced to ± 6 hours. For O_3 , HNO_3 , N_2O and CO no significant changes were observed in the intercomparison results when using either of the coincidence criteria and we have therefore chosen to use the first coincidence criteria for these gases in order to have the highest number of matched profiles. Due to the diurnal variations of ClO in the stratosphere, specific coincidence criteria, detailed in section 4.4, have been chosen for the intercomparison of ClO profiles measured by SMR and MLS.

For the gases studied in the present paper, the MLS and SMR vertical resolutions are similar (2-4 km in the stratosphere and ~ 6 km in the mesosphere). We have therefore chosen to linearly interpolate the SMR profiles as a function of log-pressure, to the fixed MLS retrieval pressure levels. Due to the rather low single-scan precisions of both instruments, the comparisons are presented as zonal means computed from coincident profiles in 30° latitude bands. We have selected two periods of measurements: the first one in September 2004 representative of austral spring and the second one in March 2005 representative of boreal spring. Sensitivity tests have shown that the results of the intercomparisons are not sensitive to the choice of the selected periods in each season. This temporal stability

is further highlighted by the consistency of the intercomparison results obtained for both seasons, 6 months apart, that are presented in this paper.

Only good quality profiles were selected for the intercomparisons. For SMR good quality means a good convergence of the retrieval and a measurement response larger than 0.75 to ensure a minor contribution of the climatological a priori profile in the retrieved value [Urban *et al.*, 2005b]. MLS data have been selected according to the quality criteria provided by Livesey *et al.* [2005]. In particular, MLS data with precision set negative are discarded ensuring that the contribution from the a priori is less than 25%. The filtering of the MLS data according to the recommendations regarding the "quality" flag eliminated bad radiance fits and the "status" flag was used to screen out MLS questionable data.

The uncertainties of the mean differences have been estimated as the standard deviation of the differences divided by the square root of the corresponding number of matched profiles. Those uncertainties combining the atmospheric variability and the precision of the individual measurements are represented by the grey solid lines (2σ) in the plots of the differences shown below. Biases are statistically significant when they are larger than the corresponding uncertainties of the mean differences.

4.2. Ozone

O₃ profiles are retrieved from the SMR 501.8 GHz band with an altitude range of 18-45 km, a vertical resolution of 2.5 km and a precision of 20-25% (~ 1.5 ppmv at the profile peak). These profiles, together with simultaneous retrievals of ClO and N₂O from the SMR 501.8 GHz band, have been used to study polar stratospheric processes [Urban *et al.*, 2004b, Ricaud *et al.*, 2005]. Version 1.5 MLS O₃ profiles are retrieved from measure-

ments by the 240 GHz radiometer with a useful altitude range extending from 215 to 0.46 hPa, a vertical resolution of ~ 2.7 km above 147 hPa and a precision of 2 to 15% (~ 0.2 ppmv at the profile peak) [Froidevaux *et al.*, 2006].

Fig. 1 displays the coincident SMR and MLS O₃ zonal means for 21-22 September 2004 and 08-09 March 2005. For both seasons, there is a good agreement between MLS and SMR zonal means in the altitude range covered by SMR (68.1-1.0 hPa). SMR is significantly biased high relative to MLS in the lower stratosphere at and below the ozone profile peak with relative biases ranging from 9% in the tropics to 18% at high latitudes. Globally, all latitudes and both seasons included, an average bias of 5 to 9% is found between 31.6 and 10.0 hPa (not shown).

The size of the error bars representative of the measured O₃ variability are larger for SMR than for MLS (Fig. 1). This difference comes primarily from a lower signal to noise ratio in the SMR data resulting in a poorer precision, but it may also come from a stronger smoothing of the O₃ profiles by the MLS retrievals. In the middle stratosphere (46.4-4.6 hPa), when all the latitudes are taken into account, the noise in the SMR data is reduced and the O₃ variability observed by both instruments are comparable. In this altitude range, fairly high (0.7-0.8) correlation coefficients between SMR and MLS O₃ highlight that both instruments are capturing similar global O₃ variations.

Global comparisons between O₃ retrieved from MLS and from 4 other limb sounders (the Stratospheric Aerosol and Gas Experiment II, SAGE II, the Halogen Occultation Experiment, HALOE, the Polar Ozone and Aerosol Measurement III, POAM III and the Atmospheric Chemistry Experiment-Fourier Transform Spectrometer, ACE-FTS) performed by Froidevaux *et al.* [2006] show an overall good agreement around the O₃ maximum and

an MLS slight overestimation of O_3 relative to HALOE ($\leq 5\%$) and to ACE-FTS ($\sim 10\%$) below 10 hPa. The results of the present SMR/MLS intercomparison are therefore indicating an overestimation of O_3 by SMR below 10 hPa rather than an underestimation by MLS.

4.3. Nitric Acid

HNO_3 profiles are retrieved from the SMR 544.6 GHz band with the Chalmers data processor version 2.0 from 18 to 45 km with a resolution of 1.5-2 km and a precision better than 1.0 ppbv [Urban *et al.*, 2006b]. Profiles retrieved from MLS are considered useful from 147 up to 3.2 hPa with a single-scan precision of 1.0-1.5 ppbv and a vertical resolution of ~ 3.5 km below 10 hPa and 4.5 km above [Froidevaux *et al.*, 2006].

The zonal mean intercomparisons for 21-22 September 2004 and 08-09 March 2005 are displayed in Fig. 2. Globally, for both seasons and in all latitude bands, the MLS and SMR profiles are in good agreement at the SMR profile peak, but SMR values are larger below the peak and smaller above it. This indicates an altitude shift of ~ 2 km between the SMR and the MLS HNO_3 profiles as a possible cause for the disagreement. Such an error may be linked to a systematic error in the simultaneous pointing and temperature/pressure retrieval from the SMR 544.6 band. Oscillations in the profiles of the differences are resulting from systematic oscillations in the MLS profiles, an MLS retrieval artifact that is reported in Livesey *et al.* [2005]. At 46.4 hPa, the lowest level reached by SMR except at high southern latitudes, the high SMR bias relative to MLS ranges from 0.2 to 1.1 ppbv. Above the profile peak, the low SMR bias is maximum at high latitudes with values reaching 3.7 ppbv and minimum in the tropics with values below 1.5 ppbv. At

4.6 hPa we reach the upper level of the useful altitude range for SMR and HNO_3 values become particularly low and even systematically negative from 3.1 hPa upwards.

In the global average, for both seasons and all latitudes included, at 46.4 hPa MLS is biased low by $\sim 8\%$ and high by $\sim 30\%$ above the profile peak (21.5-6.8 hPa). The highest correlation coefficients between MLS and SMR values ranging from 0.54 to 0.87 are found between 46.4 and 14.7 hPa highlighting the fair agreement between both instruments in tracking the HNO_3 variations in this altitude range. Above 6.8 hPa, the correlation coefficients are close to 0 because of the loss of sensitivity of the SMR measurements above ~ 35 km.

Systematic biases of 2-3 ppbv around the profile peak between MLS and ACE-FTS and of up to 3 ppbv between MLS and two different infrared balloon borne instruments are reported by *Froidevaux et al.* [2006]. These disagreements may arise from possible uncertainties in either the infrared or microwave spectroscopy used for the retrievals.

4.4. Chlorine Monoxide

SMR ClO data from the CTSO version 222 are retrieved with a vertical resolution of 2-2.5 km and a single-scan precision of 0.15-0.25 ppbv. They are estimated to be useful from 15 up to 55 km [*Urban et al.*, 2005b] . ClO profiles version 1.5 from MLS are scientifically useful from 100 to 1 hPa. They are retrieved with a vertical resolution of ~ 3 km below 10 hPa and ~ 5 km above and a precision of 0.1-0.2 ppbv.

As mentioned in section 4.1, in order to limit the impact of ClO diurnal variations on the intercomparison results, we have used tighter coincidence criteria to compare MLS and SMR ClO profiles and averaged more days of measurements for both seasons. While

the spatial coincidence criteria are the same as for the other gases, the time coincidence criterion was reduced to ± 4 hours and we have added a Solar Zenithal Angle (SZA) coincidence criterion of $\pm 2^\circ$. Furthermore, daytime ($\text{SZA} \leq 90^\circ$) and nighttime ($\text{SZA} \geq 90^\circ$) measurements were compared separately. *Stimpfle et al.*, [2004] show the sunset evolution of ClO vmr's in the lower stratosphere in the Arctic polar vortex deduced from aircraft in-situ observations. From Fig. 9 of *Stimpfle et al.*, [2004], we can estimate that a 2° SZA increase roughly coincides with a 0.1 ppbv ClO decrease. This value corresponds to the best achievable single scan precision of both SMR and MLS indicating that a $\pm 2^\circ$ SZA coincidence criterion is sufficient for comparing ClO observations from both instruments. Sunsynchronous orbiters like Odin and Aura only provide measurements at 2 local times (ascending and descending node) for every latitudinal circle and local time differences between both satellites are only sufficiently small for coincidences (SZA differences lower than 2°) to occur at high latitudes.

ClO zonal mean intercomparisons for austral and boreal springs are displayed in Fig. 3. We present the four cases for which we had enough coincidences to make sound comparisons. At high southern latitudes, the coincidences occur at sunset in spring and during early night in fall while they occur at sunrise for high northern latitudes in both seasons. The best agreement is found in the middle and upper stratosphere (21.5-1.0 hPa) where no significant biases are observed. In the lower stratosphere, except at high southern latitudes during the austral spring, MLS ClO values are systematically lower than SMR's, with the absolute bias ranging from ~ 0.15 ppbv at 46.4 hPa to ~ 0.3 ppbv at 68.1 hPa. This systematic bias between MLS and SMR is consistent with known artifacts from both instruments. On the one hand, a persistent negative bias of as much as 0.3 ppbv at all

latitudes and seasons outside of the winter polar vortices is a known artifact of MLS ClO retrievals. Taking day-night differences in the lower stratosphere eliminates the negative bias [Livesey *et al.*, 2005]. On the other hand, SMR ClO values of 0.1 up to 0.2 ppbv at high northern latitudes outside of the polar vortex during nighttime, where model simulations predict values close to zero, suggest that SMR lower stratospheric measurements may be biased high for ClO values below the detection limit of the instrument [Berthet *et al.*, 2005].

At high latitudes, during springtime, about half of the SMR and MLS pairs of matched profiles are characterized by simultaneous chlorine activation in the lower stratosphere, with ClO concentrations ranging from 0.4 to 0.8 ppbv in the northern hemisphere and from 0.8 to 1.2 ppbv in the southern hemisphere, while low ClO values are observed simultaneously in the other half. For $\sim 10\%$ of the pairs of matched profiles, probably located near the edge of the polar vortices, activation is observed by only one instrument. At high latitudes in the lower stratosphere, there is therefore a good correlation between MLS and SMR ClO observations, with correlation coefficients ranging from 0.70 to 0.95 at 46 and 68 hPa. At high southern latitudes during austral spring, both instruments measure the same mean high quantities of ClO in the lower stratosphere (0.53 ppbv) while at high northern latitudes during boreal spring, the MLS negative bias relative to SMR is clearly visible. This observation confirms the absence of bias for MLS in the polar vortex in the presence of strong chlorine activation. It also suggests that the SMR lower stratospheric bias is significantly reduced in the presence of high quantities of ClO.

4.5. Nitrous Oxide

Nitrous oxide profiles retrieved from SMR by the CTSO version 222 have a resolution of ~ 2 km and a useful altitude range from 13 to 55 km [*Urban et al.*, 2005b]. Single-scan precisions of ~ 15 ppbv in the middle and upper stratosphere worsening to 15-45 ppbv below are estimated in *Urban et al.* [2005a]. The version 1.5 N₂O MLS retrievals are considered useful from 100 to 1 hPa with a vertical resolution of roughly 4 km. An estimated precision of ~ 15 ppbv similar to SMR is reported in the 22-2.2 hPa range in *Froidevaux et al.* [2006].

The zonal mean comparisons between SMR and MLS N₂O profiles for austral and boreal springs are displayed in Fig. 4. Except at high southern latitudes in the lower stratosphere in austral spring, the agreement between both datasets is very good and the latitudinal variations are very well matched throughout the stratosphere. Between 68.1 and 10 hPa MLS is significantly biased low relative to SMR with maximum absolute differences in the range 10-20 ppbv at high and middle latitudes and 20-30 ppbv in the tropics. This is in good agreement with *Froidevaux et al.* [2006] who found that MLS was biased low by less than 20% relative to ACE-FTS in the same altitude range. Above 10 hPa no significant biases between MLS and SMR are observed. At southern high latitudes (90°-60°S) in austral spring and in the lower stratosphere (146.8-68.1hPa), MLS values are unrealistically high (up to 390 ppbv), and the differences between MLS and SMR are reaching 110 ppbv ($\sim 50\%$). This discrepancy is consistent with *Froidevaux et al.* [2006] who report that biases of up to 60 ppbv are possible in the lower stratosphere inside the polar vortex as a result of a forward model approximation.

For the global comparison (not shown), including all the latitudes and both seasons, from 146.8 to 2.1 hPa the average relative biases are smaller than 15%. From 68.1 up to 3.1

hPa, the standard deviations of the differences (12-65%) are significantly smaller than the variations measured by the instruments (30-100%) and high correlation coefficients are achieved (0.75-0.97), highlighting the ability of both instruments to capture the N₂O variations.

N₂O data from SMR have been validated by *Urban et al.* [2005a]. For the version 222 of the CTSO discussed in the present study, comparisons with balloon and aircraft data and global cross-comparisons with ILAS II (Improved Limb Atmospheric Spectrometer II) and MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) spaceborne instruments show differences smaller than 15% for N₂O values larger than 100 ppbv and smaller than 20 ppbv for N₂O values lower than 100 ppbv. The behaviour of MLS N₂O data relative to SMR is therefore consistent with the results from the SMR validation study by *Urban et al.* [2005a].

4.6. Carbon Monoxide

The first CO retrievals from SMR described in *Dupuy et al.* [2005] were produced with the CTSO version 223. Comparisons of those first SMR CO data with several profiles from the ACE-FTS instrument have shown good agreement [*Jin et al.*, 2005]. The SMR CO profiles discussed here were produced by the CTSO version 225. The main difference with version 223 is that temperature is no longer retrieved simultaneously with CO and O₃. Correlation between temperature and O₃ retrievals in version 223 was responsible for anomalously low stratospheric O₃ concentrations. Comparisons with MLS O₃ have shown that this is not the case anymore with the version 225 (not shown). CO profiles are retrieved from the SMR 576.9 GHz band with a resolution of 2-4 km below ~65 km degrading to ~6 km above and a single-scan precision better than 25 ppbv in

the stratosphere increasing up to 1-2 ppmv at the top of the mesosphere (~ 80 km). First results from CO measured by MLS are described in *Filipiak et al.* [2005]. Their characteristics are roughly similar to those of SMR with a single-scan precision ranging from ~ 30 ppbv in the upper-troposphere and lower stratosphere to 0.3-3 ppmv in the mesosphere. The vertical resolution of the retrievals range from ~ 4 km in the upper troposphere-lower stratosphere to 6 km in the upper mesosphere. Strong oscillations in the vertical distributions are noticeable in the zonal distributions displayed in *Filipiak et al.* [2005]. They are attributable to a problem in the regularisation of the retrievals which is still under investigation.

The intercomparison of MLS and SMR CO profiles for 18-19 September 2004 and 23-24 March 2005 are displayed in Fig. 5. Above 0.1 hPa, MLS is systematically biased high relative to SMR by 60 up to 250%. This result is consistent with comparisons between CO from MLS and ACE-FTS performed by *Froidevaux et al.* [2006] that show a MLS 50-100% positive bias in the upper mesosphere/lower thermosphere. From the middle stratosphere (10 hPa) to the middle mesosphere (0.1 hPa) the most important discrepancies come from the strong oscillations present in the MLS profiles mirrored in the differences. Nevertheless, in this altitude range, strong oscillations coincide with large uncertainties in the mean differences and no significant biases are observed. At 31.6 and 21.5 hPa in the tropics (30°S - 30°N), MLS values are systematically negative resulting in a low bias relative to SMR (100-160%). This is a known artifact in the MLS CO retrievals [*Livesey et al.*, 2005]. Finally, in the lower stratosphere (68.1-31.6 hPa) at high latitudes in fall, MLS is measuring CO values larger than SMR by up to 120%. This high MLS bias have been observed from comparisons with ACE-FTS measurements [*Froidevaux et*

al., 2006] in both hemispheres. It is thought to be caused by weak HNO_3 lines in the frequency band used to measure CO that may impact the CO retrievals in the presence of high concentrations of HNO_3 as is the case at high latitudes [Livesey *et al.*, 2005]. The absence of such a bias between MLS and SMR at high latitudes in spring, with even higher HNO_3 concentrations than in fall, may be due to the residual contribution of the a priori profiles used for the SMR retrievals, characterised by elevated CO concentrations in the lower stratosphere in the polar vortices.

5. Summary and conclusions

The global intercomparison of Odin/SMR and Aura/MLS version 1.5 data has generally demonstrated good agreement for the 5 gases studied.

In the stratosphere, we found good agreement between O_3 retrieved from the SMR 501.8 GHz band (CTSO version 222) and MLS data. At and below the profile peak, SMR is slightly overestimating O_3 ($\leq 10\%$) relative to MLS. Since MLS O_3 show a good overall agreement with several other instruments [Froidevaux *et al.*, 2006], this result points to a clear overestimation of O_3 by SMR. Throughout the middle stratosphere, global O_3 variations observed by both instruments are consistent with each other.

Above the profile maximum, SMR HNO_3 profiles (Swedish data processor version 2.0) are biased low by $\sim 30\%$ relative to the MLS profiles while they are biased high below the profile peak. A systematic error in the SMR pointing retrieval in the 544.6 GHz band may partly explain this disagreement. Between 46.4 and 14.7 hPa, the global variations of HNO_3 observed by both instruments are in fair agreement (correlation coefficients ranging from 0.5 to 0.9).

Using tight time and SZA coincidence criteria, necessary because of the ClO diurnal

variations, comparisons of MLS and SMR (CTSO version 222) ClO profiles were only possible at high latitudes. Zonal means from SMR and MLS are in good agreement in the upper stratosphere around the profile peak (21-1 hPa) where no significant biases were encountered. In the lower stratosphere, in the absence of chlorine activation, MLS underestimates ClO by up to 0.3 ppbv relative to SMR. This difference results from known biases from both instruments in the presence of very low ClO quantities. Those biases are significantly reduced in the polar vortices in the presence of chlorine activation.

N₂O data from MLS and SMR (CTSO version 222) are in excellent agreement except at high southern latitudes in spring where a known MLS retrieval artifact results in unrealistically high N₂O concentrations. Between 68.1 and 10 hPa, the low MLS bias relative to SMR is consistent with results from the extensive validation study of SMR N₂O by *Urban et al.* [2005a]. The consistency between the N₂O variations captured by both instruments is demonstrated by correlation coefficients larger than 0.75.

Comparisons between MLS and SMR (CTSO version 225) CO profiles have confirmed most of the MLS retrieval artifacts: a high bias in the upper mesosphere, strong oscillations from the middle stratosphere to the middle mesosphere, negative values in the tropics around 30 hPa. The MLS positive bias at high latitudes in the lower stratosphere, observed in comparisons with ACE-FTS, was only visible in fall, highlighting a possible SMR retrieval artifact in spring.

Acknowledgments. Odin is a Swedish-led satellite project funded jointly by the Swedish National Space Board (SNSB), the Canadian Space Agency (CSA), the National Technology Agency of Finland (Tekes), and the Centre National d'Etudes Spatiales

(CNES). This work was funded in France by the Centre National de la Recherche Scientifique (CNRS), Ministre de l'Education Nationale, de la Recherche et de la Technologie (MENRT), CNES, and the Programme National de Chimie Atmosphérique (PNCA). Brice Barret is funded by the European Commission within the SCOUT-O3 programme. Odin data processed by the French CTSO version 222 and by the Swedish data processor version 2.0 are stored in the Ether French atmospheric data base (<http://ether.ipsl.jussieu.fr>). Work at the Jet Propulsion Laboratory, California Institute of Technology, was done under contract with the National Aeronautics and Space Administration. M. J. Filipiak is supported by the UK Natural Environment Research Council.

References

- Baron, P., P. Ricaud, J. de la Noe, P. Eriksson, F. Merino, M. Ridal, and D. Murtagh, Studies for the Odin sub-millimetre radiometer. II. Retrieval methodology (2002), *Can. J. Phys.*, 80(4), 341-356.
- Berthet G., P. Ricaud, F. Lefvre, E. Le Flochmon, J. Urban, B. Barret, N. Lauti, E. Dupuy, J. De La No, D. Murtagh, Nighttime chlorine monoxide observations by the Odin satellite and implications for the ClO/Cl₂O₂ equilibrium (2005), *Geophys. Res. Lett.*, 32, L11812, doi:10.1029/2005GL022649.
- Cofield R. E., and P. C. Stek, Design and field-of-view calibration of 114-660 GHz optics of the Earth Observing System Microwave Limb Sounder (2006), *IEEE Trans. Geosci. Remote Sensing*, 44(5), 1166-1181.
- Dupuy, E., et al., Strato-mesospheric measurements of carbon monoxide with the Odin Sub-Millimetre Radiometer: Retrieval and first results (2004), *Geophys. Res. Lett.*, 31,

L20101, doi:10.1029/2004GL020558.

Eriksson, P., F. Merino, D. Murtagh, P. Baron, P. Ricaud, and J. de la Noe, Studies for the Odin sub-millimetre radiometer: I. Radiative transfer and instrument simulation (2002), *Can. J. Phys.*, *80*(4), 321-340.

Eriksson, P., C. Jimenez, and S. Buehler, Qpack: A tool for instrument simulation and retrieval work (2005), *J. Quant. Spectrosc. Radiat. Transfer*, *91*, 47-61, doi:10.1016/j.jqsrt.2004.05.050

Filipiak, M. J., R. S. Harwood, J. H. Jiang, Q. Li, N. J. Livesey, G. L. Manney, W. G. Read, M. J. Schwartz, J. W. Waters, and D. L. Wu, Carbon monoxide measured by the EOS Microwave Limb Sounder on Aura: First results (2005), *Geophys. Res. Lett.*, *32*, L14825, doi:10.1029/2005GL022765.

Frisk, U., et al., The Odin satellite - I. Radiometer design and test (2003), *Astron. Astrophys.*, *402*(3), 27-34.

Froidevaux, L., et al., Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1106-1121.

Olberg, M., et al., The Odin satellite - II. Radiometer data processing and calibration (2003), *Astron. Astrophys.*, *402*(3), 35-38.

Jarnot, R. F., V. S. Perun, and M. J. Schwartz, Radiometric and spectral performance and calibration of the GHz bands of EOS MLS (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1131-1143.

Jin, J. J., et al., Co-located ACE-FTS and Odin/SMR stratospheric-mesospheric CO 2004 measurements and comparison with a GCM (2005), *Geophys. Res. Lett.*, *32*, L15S03, doi:10.1029/2005GL022433.

- Livesey, N. J., et al., Earth Observing System (EOS) Microwave Limb Sounder (MLS), Version 1.5 Level 2 data quality and description document (2005), Jet Propulsion Laboratory, Tech. Rep., D-32381, available on the MLS website, <http://mls.jpl.nasa.gov>.
- Livesey, N. J., W. Van Snyder, W. G. Read, and P. A. Wagner, Retrieval algorithms for the EOS Microwave Limb Sounder (MLS) instrument (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1144-1155.
- Merino, F., D. P. Murtagh, M. Ridal, P. Eriksson, P. Baron, P. Ricaud and J. de La Noe, Studies for the Odin sub-millimetre radiometer: III. Performance simulations, (2002), *Can. J. Phys.*, *80*, 357-373.
- Murtagh, D. P., et al., An overview of the Odin atmospheric mission, (2002), *Can. J. Phys.*, *80*, 309-319.
- Pickett, H. M., Microwave Limb Sounder THz Module on Aura (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1122-1130.
- Rodgers, C. D., Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation, (1976), *Reviews of Geophysics and Space Physics*, *14*, 609-624.
- Ricaud, P., et al., Polar vortex evolution during the 2002 Antarctic major warming as observed by the Odin satellite (2005), *J. Geophys. Res.*, *110*, D05302, doi:10.1029/2004JD005018.
- Schoeberl, M. R., A. R. Douglass, E. Hilsenrath, P. K. Bhartia, J. Barnett, R. Beer, J. Waters, M. Gunson, L. Froidevaux, J. Gille, P. F. Levelt and P. DeCola, Overview of the EOS Aura Mission (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1066-1074.

- Stimpfle, R. M, D. M. Wilmouth, R. J. Salawitch and J. G. Anderson, First measurements of ClOOCl in the stratosphere: The coupling of ClOOCl and ClO in the Arctic polar vortex (2004), *J. Geophys. Res.*, *109*, D03301, doi:10.1029/2003JD003811.
- Urban, J., et al., Moliere (v5): a versatile forward- and inversion model for the millimeter and sub-millimeter wavelength range (2004a), *J. Quant. Spectrosc. Radiat. Transfer*, *83*, 529-554.
- Urban, J., et al., The northern hemisphere stratospheric vortex during the 2002-2003 winter: Subsidence, chlorine activation and ozone loss observed by the Odin Sub-Millimetre Radiometer (2004b), *Geophys. Res. Lett.*, *31*, L07103, doi:10.1029/2003GL019089.
- Urban, J., et al., Odin/SMR limb observations of stratospheric trace gases: Validation of N₂O (2005a), *J. Geophys. Res.*, *110*, D09301, doi:10.1029/2004JD005394.
- Urban, J., et al., Odin/SMR limb observations of stratospheric trace gases: Level 2 processing of ClO, N₂O, HNO₃, and O₃ (2005b), *J. Geophys. Res.*, *110*, D14307, doi:10.1029/2004JD005741.
- Urban, J., et al., Global observations of middle atmospheric water vapour by the Odin satellite: An overview (2006a), *Planetary and Space Science*, in revision.
- Urban, J., et al., Odin/SMR Limb Observations of Trace Gases in the Polar Lower Stratosphere during 2004-2005 (2006b), Proc. ESA Atmospheric Science Conference, 8-12 May 2006, Frascati, Italy, European Space Agency publications.
- Waters, J. W., et al., The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite (2006), *IEEE Trans. Geosci. Remote Sensing*, *44*(5), 1075-1092.

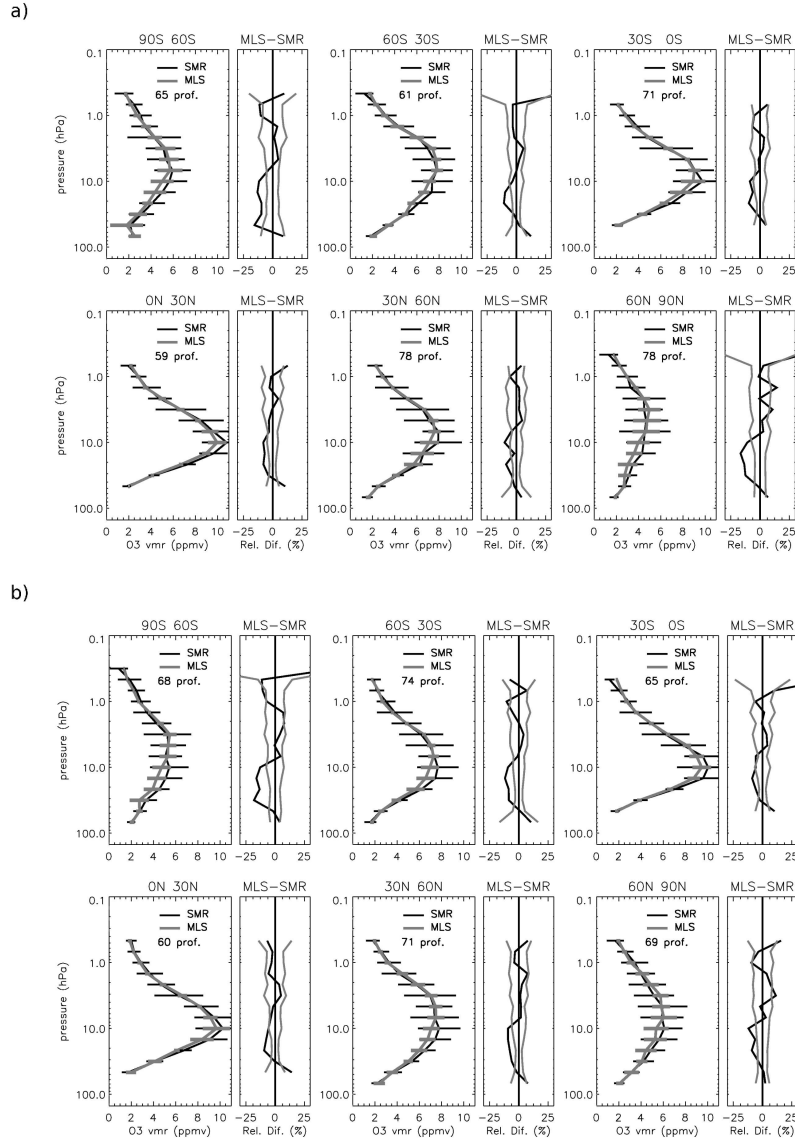
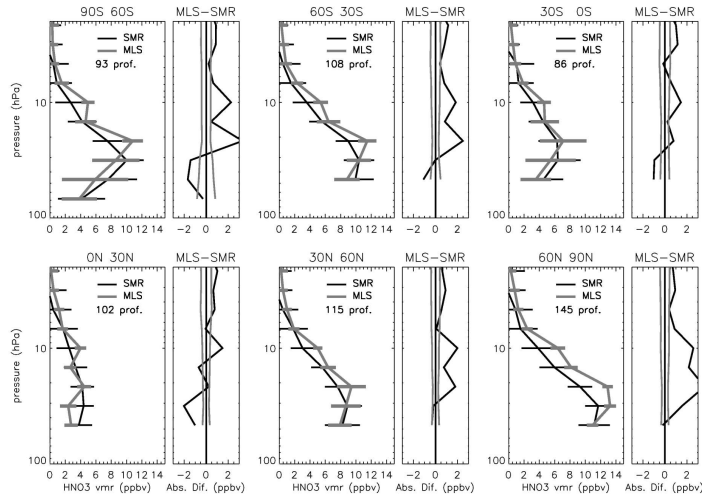


Figure 1. Zonal mean comparisons between O_3 retrieved from the 501.8 GHz SMR band by the CTSO version 222 and MLS O_3 version 1.5 by bands of 30° latitude for measurements performed a) 21-22 September 2004, b) 08-09 March 2005. For each band, left panel: average of coincident profiles from SMR (solid black) and from MLS (dashed grey). Error bars represent the standard deviation of the profiles. Right panel: average differences (MLS minus SMR) expressed in percent relative to the mean SMR profile (solid) and standard deviations of the differences (dashed). The grey solid lines represent the uncertainties on the mean differences (2σ). The number of coincident profiles used for the comparisons are indicated for each latitude band in

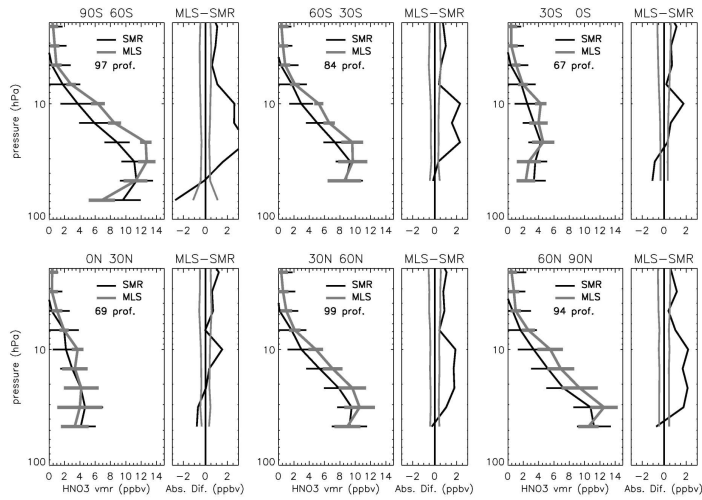
Table 1. SMR and MLS data products used for the intercomparisons.

product	SMR		MLS	
	Band	Version	Radiometer	Version
O ₃	501.8 GHz	CTSO 222	R3	1.5
HNO ₃	544.6 GHz	Chalmers 2.0	R3/R2	1.5
ClO	501.8 GHz	CTSO 222	R4	1.5
N ₂ O	501.8 GHz	CTSO 222	R4	1.5
CO	576.9 GHz	CTSO 225	R3	1.5

a)



b)

**Figure 2.** Same as Figure 1 except for HNO₃ retrieved by the Chalmers data processor version 2.0 from the 544.6 GHz SMR band.

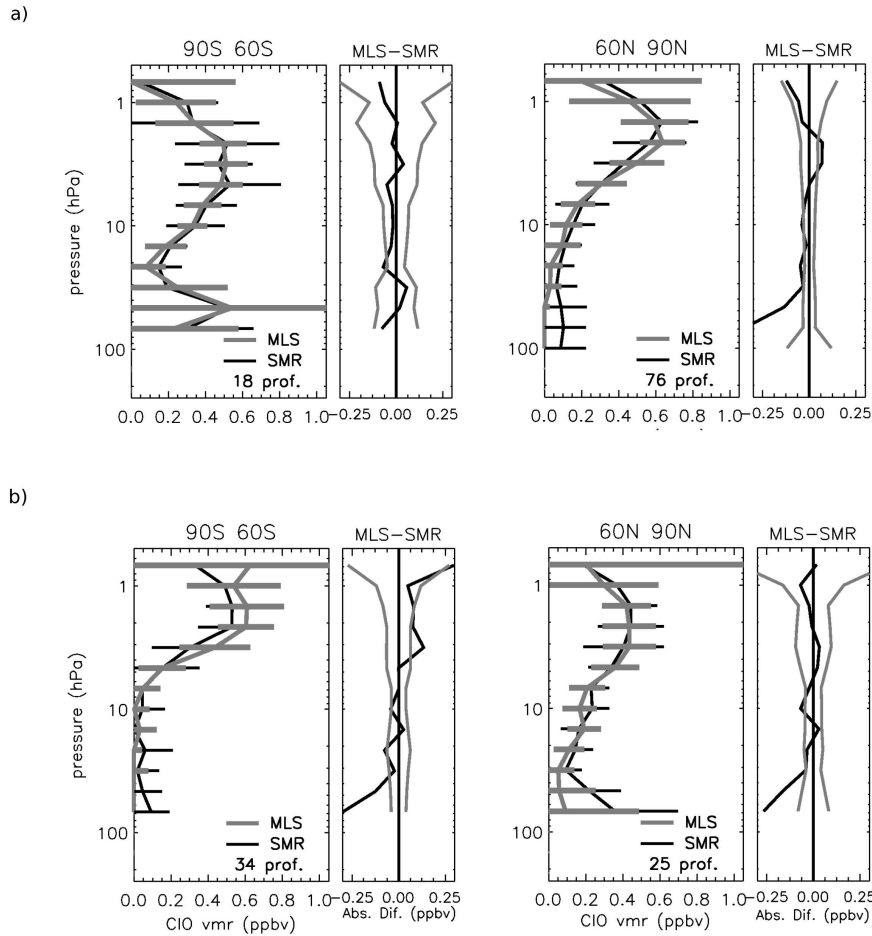


Figure 3. Same as Figure 1 except for CIO comparisons for measurements performed a) 31 August-01 September, 06-07, 16, 21-22 September, and 03-04, 06-07, 09-10 October 2004, b) 27-28 February, 08-09, 23-24 and 29-30 March 2005. Comparisons concern measurements performed at different periods of the day: a) 90°S-60°S (upper left) sunset ($84.5^\circ \leq \text{SZA} \leq 89.5^\circ$), 60°N-90°N (upper right) sunrise ($73^\circ \leq \text{SZA} \leq 88.5^\circ$), b) 90°S-60°S (lower left) early night ($93^\circ \leq \text{SZA} \leq 103^\circ$), 60°N-90°N (lower right) sunrise ($80^\circ \leq \text{SZA} \leq 89^\circ$). In the right panels, differences are expressed in absolute units (ppbv).

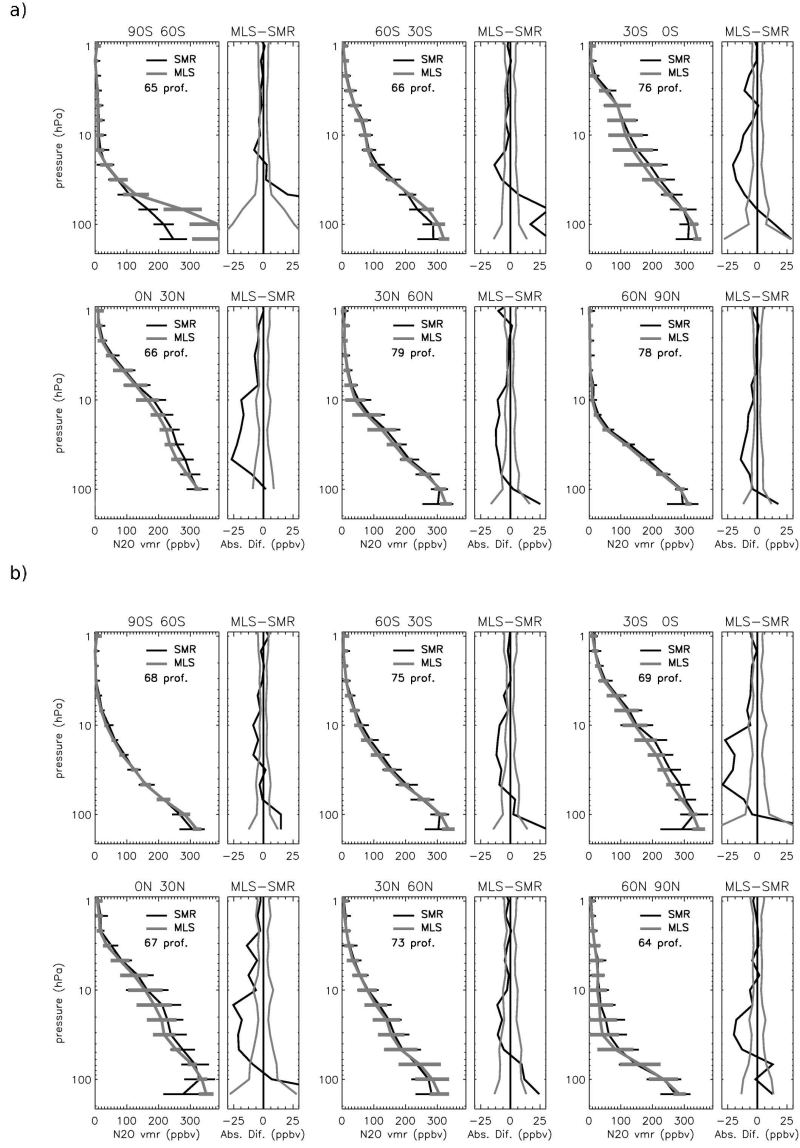


Figure 4. Same as Figure 1 except for N_2O comparisons. In the right panels, differences are expressed in absolute units (ppbv)

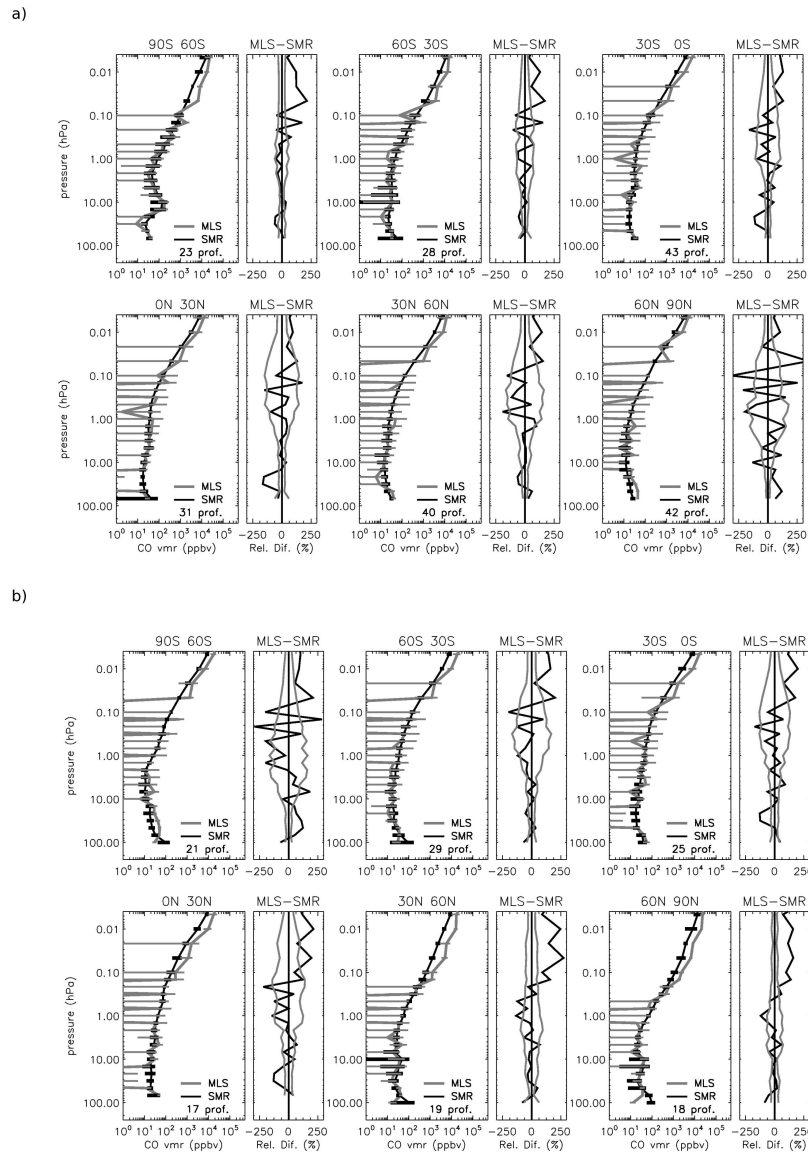


Figure 5. Same as Figure 1 except for CO retrieved from the 576.9 GHz SMR band by the CTSO version 225 for measurements performed a) 18-19 September 2004 b) 23-24 March 2005.

In the left panels, note the logarithmic scales.